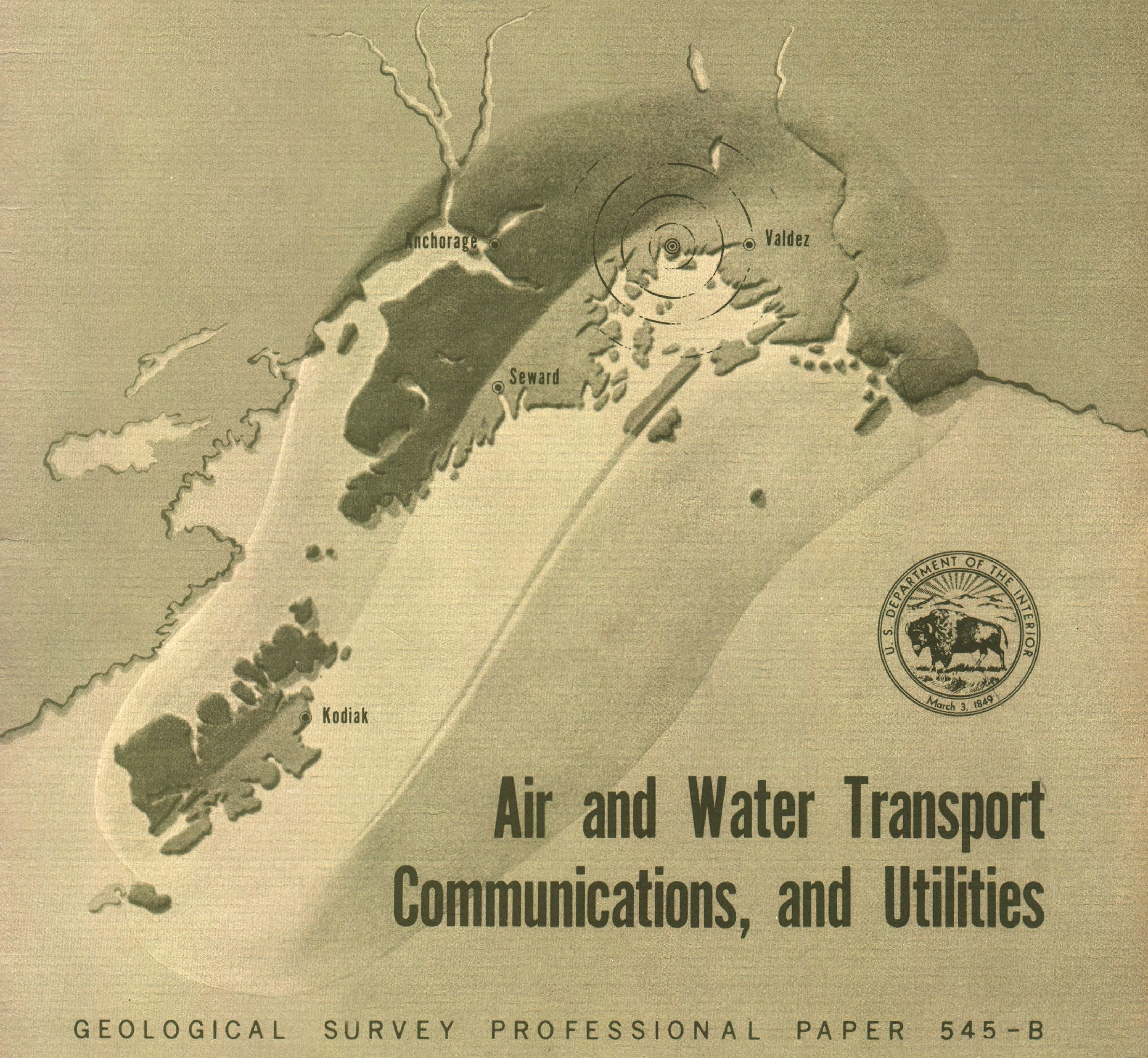
The Alaska Earthquake

March 27, 1964

Effects on Transportation and Utilities



Air and Water Transport Communications, and Utilities

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THE ALASKA EARTHQUAKE, MARCH 27, 1964:
EFFECTS ON TRANSPORTATION, COMMUNICATIONS, AND UTILITIES

Effects of the Earthquake Of March 27, 1964, on Air and Water Transport, Communications, and Utilities Systems In South-Central Alaska

By EDWIN B. ECKEL

A description of the disruption and damage that all systems sustained from seismic vibrations and tectonic changes and from the slides, waves, and fires caused by the earthquake

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of its investigations of the Alaska earthquake of March 27, 1964, in a series of six professional papers. Professional Paper 545 describes the effects of the earthquake on transportation, communications, and utilities. Other professional papers describe the effects on communities, regions, and the hydrologic regimen; and one gives the history of the field investigations and reconstruction effort.

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1.—South-central Alaska, showing main power (short-dashed) and gas-transmission (solid) lines and principal communities whose ports, airports, or utility systems were damaged by the earthquake. Land to left of zero land level change line was generally lowered; land to right of line was raised.

EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964, ON AIR AND WATER TRANSPORT, COMMUNICATIONS, AND UTILITIES SYSTEMS

By Edwin B. Eckel

ABSTRACT

The earthquake of March 27, 1964, wrecked or severely hampered all forms of transportation, all utilities, and all communications systems over a very large part of south-central Alaska. Effects on air transportation were minor as compared to those on the water, highway, and railroad transport systems. A few planes were damaged or wrecked by seismic vibration or by flooding. Numerous airport facilities were damaged by vibration or by secondary effects of the earthquake, notably seismic sea and landslide-generated waves, tectonic subsidence, and compaction. Nearly all air facilities were partly or wholly operational within a few hours after the earthquake.

The earthquake inflicted enormous damage on the shipping industry, which is indispensable to a State that imports fully 90 percent of its requirements—mostly by water—and whose largest single industry is fishing. Except for those of Anchorage, all port facilities in the earthquake-affected area were destroyed or made inoperable by submarine slides, waves, tectonic uplift, and fire. No large vessels were lost, but more than 200 smaller ones (mostly crab or salmon boats) were lost or severely damaged. Navigation aids were destroyed, and hitherto well-known waterways were greatly altered by uplift or subsidence. All these effects wrought far-reaching changes in the shipping economy of Alaska, many of them to it betterment.

Virtually all utilities and communications in south-central Alaska were damaged or wrecked by the earthquake, but temporary repairs were effected in remarkably short times. Communications systems were silenced almost everywhere by loss of power or by downed lines; their place was quickly taken by a patchwork of self-powered radio transmitters. A complex power-generating system that served much of the stricken area from steam, diesel, and hydrogenerating plants was disrupted in many places by vibration damage to equipment and by broken transmission lines. Landslides in Anchorage broke gas-distribution lines in many places, but the main transmission line from the Kenai Peninsula was virtually undamaged. Petroleum supplies were disrupted, principally by breakage or loss of storage tanks caused by seismic vibration, slides, waves, and fire. Water-supply and sewer lines were also broken in many towns.

INTRODUCTION

The earthquake of March 27, 1964, wrecked or severely hampered all forms of transportation, all utilities, and all communications systems over a very large part of south-central Alaska.

The relationship of geology to the earthquake's effects on the highway and railroad systems was studied in detail by Reuben Kachadoorian and by D. S. McCulloch and M. G. Bonilla, respectively, and their findings will be reported separately in this series. Similarly, effects on water supplies, from both surface and underground sources, are described in detail by Waller (1966a, b). The earthquake damage to one of the chief sources of electric power in the Anchorage area—the U.S. Bureau of Reclamation's Eklutna Hydroelectric Project—is described by Logan (1967), and a novel method of tracing breaks in underground utility lines by means of a portable television camera is described by Burton (in Logan, 1967).

In order to complete the picture of the earthquake's effects on the works of man, its effects on air and water transport and on utilities are briefly summarized here. The principal places affected are shown on figure 1. The report is necessarily a synthesis of information collected and reported by others in the course of investigating various regional or topical phases of the earthquake story; most of these sources are listed in the bibliography. In addition, several of the writer's colleagues, particularly Reuben Kachadoorian and George Plafker, have contributed many pieces of information; this compilation would have been far less complete without their help.

AIR TRANSPORT

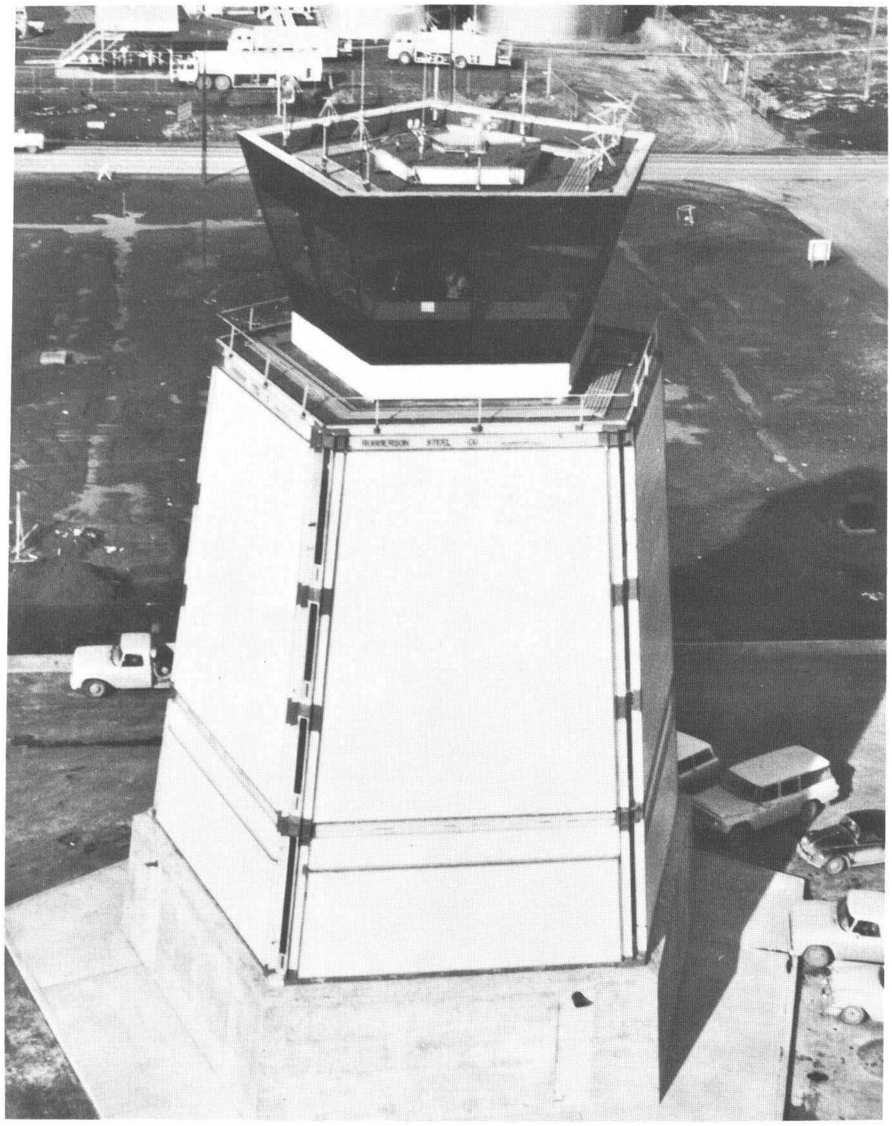
The earthquake's effects on air transportation were minor as compared to those on the water, highway, and railroad transport systems. This minor damage was doubly fortunate, for the earthquake catastrophe itself made immediate massive airlifts essential. Moreover, air transport of people and goods is much more important in Alaska than elsewhere in the United States. In addition to the great military and commercial air capability, Alaska has one aircraft for each 156 people; one person in every 55 is a licensed pilot.

The few planes that were airborne at the moment the earthquake struck were of course not damaged, though some had communications difficulties and some were diverted to other airports. Planes on the ground or in hangars were damaged by being battered against each other or against fixed objects; at least one plane was badly damaged by water immersion on a ramp at the Kodiak Naval Station, one was destroyed at Kodiak, and several small planes were wrecked by waves at Seward.

Damages to airport facilities were caused in part by earthquake vibrations, in part by secondary effects, notably waves, and in part by tectonic subsidence and compaction. Numerous buildings

2.—Control tower at Anchorage International Airport, collapsed by earthquake shaking. Photograph by Federal Aviation Agency.

were damaged and their utilities disrupted by seismic shaking. The wrecked control tower at Anchorage International Airport was one of the greatest single losses, caused by vibration, that directly affected the aviation system (figs. 2, 3). Some subsidiary buildings, however, such as the military hospital at Elmendorf Air Base, sustained greater damages in terms of total repair costs. Many runways, aprons, and taxiways were cracked and made uneven by shaking and the resultant differential consolidation of alluvial materials or artifical fill. Hangars, seaplane ramps, and parts of the runways at Kodiak Naval Station were flooded by a series of seismic sea waves, and a few smaller airstrips were either destroyed by waves or were subjected to partial flooding by high tides due to regional subsidence. Despite all these difficulties, total damage to Alaska's air facilities amounted to only a few million dollars, as compared with more than $100 million worth of damages to the water, rail, and highway systems. More significant than the relatively small dollar losses, perhaps, is the fact that nearly all air facilities were partly or wholly operational within a few hours after the earthquake. This made possible the enormous air transport of people, food, and supplies that were required at once.



3.—New control tower for Anchorage International Airport, built by Federal Aviation Agency at a cost of $850,000. One of the first of the new O-type towers in the nation, it was operational by February, 1965. Photograph by Federal Aviation Agency.

ANCHORAGE

All three major airfields at Anchorage—Elmendorf Air Force Base, Anchorage International Airport, and Merrill Field—escaped the huge landslides that wrought so much havoc in parts of Anchorage (Hansen, 1965), but all sustained some degree of damage by earthquake vibration. Merrill Field, heavily used by the Civil Air Patrol and by private planes, was back in full operation within an hour of the quake, and served as a control center for all air traffic in the Anchorage area while control facilities at Elmendorf and Anchorage International were being repaired.

The two chief military installations at Anchorage—Fort Richardson and Elmendorf Air Force Base—are on a broad plain north of the city. They are founded on thick outwash gravels of the Elmendorf moraine (Miller and Dobrovolny, 1959). Except for a few minor slipouts along the north bluff of Ship Creek, there were no landslides of the kind that devastated nearby Government Hill and other parts of Anchorage (Hansen, 1965), and there were but few ground cracks. Many large and small buildings on both military reservations, however, sustained structural damage from shaking by the earthquake. Those directly connected with air

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transportation were two of the hangars at Elmendorf and the control tower at that base. Disrupted power and communications facilities, of course, added to the difficulties of maintaining the military air capability. Despite these difficulties, the Elmendorf airfield remained operational; even during the initial shaking, and despite violent swaying, the control tower maintained radio contacts. Soon after the shaking subsided, however, air-traffic control was transferred to facilities installed in a parked aircraft, and 2 days after the earthquake the aircraft was replaced by a mobile control tower that was used until the damaged tower was rebuilt.

Anchorage International Airport is southwest of the city. It is built on a thin layer of silt that overlies older glacial deposits. These, in turn, probably overlie the Bootlegger Cove Clay, whose weakness under earthquake stresses led to the disastrous landslides at Turnagain Heights 2 miles north of the airfield. Anchorage Airport is too far inland to have had similar landslides, but it sustained significant damage from the earthquake shocks. The runways and taxiways cracked in a few places, but were easily resurfaced. The greatest single loss was the new 50-foot reinforced-concrete control tower, which toppled to the ground, carrying one operator to his death. The tower was later replaced (figs. 2, 3). After the disaster, traffic controllers first used a parked small plane to talk with Merrill Field, which was still operational. Later, the tower of the nearby Lake Hood seaplane facility was used by Anchorage air control. A hangar and part of the 3-story steel-frame terminal building also collapsed during the earthquake. Among other facilities, the Weather Bureau station in the terminal building was demolished.

CORDOVA

At Cordova airport the main 150-foot-wide surfaced runway was virtually unaffected by the earthquake, but the bordering runway aprons, which are each 150 feet wide, and the nearby F.A.A. (Federal Aviation Agency) facilities sustained moderate damage from ground cracking; the violent ground motion caused powerlines to snap. The airport and appurtenant facilities are on thick alluvial deposits of the flat poorly drained Copper River delta 13 miles east of Cordova. Drainage ditches 10–12 feet deep and about 75 feet wide parallel the airstrip on either side. Seismic shaking caused the aprons to spread laterally toward the bordering ditches with resultant cracking of the apron surfaces. Most of the cracks thus formed were extension cracks, as much as 8 inches wide, that were parallel to the edge of the airstrip.

A single ground crack split the reinforced-concrete slab floor of the F.A.A. office building and control tower at the airport, but did not interrupt operation of the facility. The fact that the crack was parallel to, and about 20–50 feet from, a small creek suggests that it resulted from lateral movement of the surficial deposits toward the creek channel. Underground water and steam lines at the F.A.A. facility were broken in so many places by ground cracking that most of the system had to be replaced.

KODIAK NAVAL STATION

Air facilities at Kodiak Naval Station, which serves both military and scheduled civilian traffic, were moderately damaged by flooding, tectonic subsidence, and vibration. Damage to the naval port facilities is described on page B15.

The earthquake vibrations cracked water mains and caused other minor damage. A series of seismic sea waves that began about 45 minutes after the earthquake inundated many buildings, including the three main hangars and the central power station. The inundating waters damaged runway lights, the Operations Control generator, the Tactical Air Command and Navigation generator, and the Rawin Aerological Building. These structures are essential in controlling the smooth flow of air traffic in and out of the naval station. Debris and ice were dumped on aprons in the hangar area. The seaplane ramps on Womens Bay were partly submerged at high tides, owing to the tectonic subsidence of more than 5 feet. The main runways were only damaged near the seaward ends, but asphalt taxiways were cracked, either by the vibration itself or as a result of consolidation of underlying materials (Tudor, 1964; Stroh, 1964; Kachadoorian and Plafker, 1967). The seaward end of the main runway was subjected to erosion by high tides as a result of regional subsidence; this erosion will be a continuing problem.

A sheet-pile bulkhead between two seaplane ramps on Womens Bay failed and moved outward at a point where the piles had been driven into soft sediments in an old channel (Stroh, 1964).

Hangars and apron slabs at the naval station were built on artifical fill approximately 17 feet thick; heavier structures were supported by piles. Differential consolidation of the fill, plus scour by receding seismic sea

4.—Tectonic subsidence required raising of airstrip at Seldovia. U.S. Army photograph.

waves, led to settlement at one corner of a hangar. More important, settlement of aprons in front of hangar doors caused formation of "lips" from 1 to 6 inches high that made it difficult to move planes in and out of the hangars. These conditions were repaired by constructing wooden ramps and later by raising the apron slabs by injection of grout beneath them (Stroh, 1964).

The Kodiak city airstrip was undamaged. However, all installations of Kodiak Airways, which were along the waterfront in downtown Kodiak, were totally destroyed. Seaplane ramps, hangars, offices, and one aircraft were swept away by seismic sea waves. For more than a year after the earthquake, aircraft operated out of the city airport while waterfront facilities were being rebuilt.

KENAI PENINSULA

Most of the airstrips on the Kenai Peninsula were damaged by vibration, surficial settlement, and tectonic subsidence. Parts of the Seldovia airstrip had to be built up as much as 4–5 feet, at an estimated cost of $600,000, to raise the strip above tide level (fig. 4). Runways at Ninilchik, Kenai, Soldatna, and Hope sustained minor cracks. The airport at Homer was undamaged, but new construction work there was delayed, and made more costly, when the once-ample source of gravel on Homer Spit became difficult to obtain because of tectonic subsidence and consolidation of the spit materials. The only undamaged airstrip on the Kenai Peninsula was the one at Lawing.

SEWARD

Some ground cracks formed on the gravel-surfaced runway at Seward, and the runway drainage system required repair. Several planes on the field were smashed by waves. Regional subsidence, aided by compaction of deltaic sediments at the head of Resurrection Bay, led to partial submergence of the Seward airstrip by high tides. The control tower, which had been put out of commission by waves and the general power failure, was reestablished by noon of March 28, 1964, operating on batteries. It was desperately needed, for aircraft provided the only means of movement in and out of Seward for some days (Fay, 1964; Lemke, 1967).

WHITTIER

The 2,200-foot northeast-trending airstrip at Whittier was severely damaged and became unusable after the earthquake. The airstrip lies on deltaic deposits at the head of Passage Canal nearly a mile west of Whittier. The eastern 500 feet of the strip was constructed on fill that extended into Passage Canal. During the earthquake, the end of this 500-foot section slid into the canal. In addition, regional subsidence, differential compaction of the fill, and landslide-generated waves severely damaged the part of the fill section that did not slide into Passage Canal. The loss of 500 feet of airstrip was great enough to prevent use of the strip by other than small single-engine aircraft (Kachadoorian, 1965).

OTHER AIRPORTS

Small airstrips at Chitina, Portage, Palmer, and Thompson Pass and the South Campbell strip at Anchorage had minor cracks in the runways. Airstrips at Talkeetna, Gakona, Gulkana, Tazlina, and Wasilla were not damaged.

Yakutat airport, situated on a glacial-outwash plain some 280 miles east of the earthquake epicenter, sustained minor damage to the concrete runways and ramp as a result of differential movement of the slabs during the shaking. Long-period ground waves also caused minor damage to two huge sliding hangar doors weighing several tons, each of which rolled back and forth, banging against the hangar sides.

A few small cracks also were found in the gravel runway of the Yakataga airport about half way between Yakataga and the earthquake epicenter.

The strip at Girdwood, on Turnagain Arm, was subjected to tidal flooding by the tectonic subsidence and compaction of the sediments (Federal Aviation Agency, 1965). Air-navigation aids at nearby Portage and at Hinchinbrook Island in Prince William Sound required restoration. At Valdez, the runway and parking areas were cracked and required grading, but remained in usable condition.

The Federal Aviation Agency's dock at Woody Island, near Kodiak, was so damaged by seismic sea waves that it had to be replaced. The airstrip at Afognak in the Kodiak Island group was inundated repeatedly by waves, and several hundred feet of it was permanently flooded as a result of tectonic subsidence and surficial compaction. A new airstrip was built at the new town of Port Lions on Kodiak Island where the former inhabitants of Afognak were relocated. Gravelled airstrips at Old Harbor and Ouzinkie were partly submerged by tectonic subsidence and local differential compaction of the sediments. They were later repaired and somewhat enlarged by filling and resurfacing.

In all, the Federal Aviation Agency inspected 64 airports throughout the stricken area. Of these, 13 had sustained runway and taxiway damage, including broken underground cables (Federal Aviation Agency, 1965).

SHIPPING

The shipping industry is indispensable to Alaska, because fully 90 percent of all civilian and military requirements must be imported, nearly all by water. Fisheries, moreover, constitute the State's largest single industry—all of it dependent on water transport, from movement of catch and supplies to canneries to final export of the product.

The earthquake inflicted enormous damage on the water-transportation industry. In all south-central Alaska, only the port at Anchorage remained operational, and even it was temporarily incapacitated and was restricted in its operations for some time.

Damage to port facilities at Anchorage, Seward, Valdez, Homer, *Kodiak*, Cordova, Whittier, and Seldovia amounted to about $30 million. This figure includes private and public docking facilities only, and not such waterside facilities as canneries. Damage to these facilities was primarily due to submarine landslides and waves generated by them, seismic sea waves, compaction of sediments, and regional subsidence.

Whittier, Seward, and Valdez are the only all-weather ice-free ports in Alaska that have access to the interior of the State. Whittier and Seward are terminals for The Alaska Railroad and Valdez for the Alaska Highway. Anchorage is not an ice-free port and until the earthquake was only used during the summer months. The destruction of the Whittier, Seward and Valdez ports therefore created a serious problem in the movement of supplies, food, and material to the interior of the State. Sitka, on Baranof Island, was the only port in southeast Alaska that reported significant damage. Docks and other harbor structures there were struck by seismic sea waves, and about $1 million in damage was done.

No large vessels were destroyed though some had narrow escapes. In general, vessels at sea were undamaged, but a few experienced bumps that felt to the crews as if their ships had run aground. A few free-floating small boats were capsized and sunk. Most of the boats that were lost, however, were tied up at docks, were in small-boat harbors where they were engulfed by giant waves, or were involved in the submarine slides that destroyed several ports. When the earthquake struck, 820 vessels of more than 5 tons and 2,850 smaller boats were operating in south-central Alaska (Office of Emergency Planning, 1964). Of these, more than 200 vessels, most of them crab or salmon boats, were lost or severely damaged. Many seafood-processing plants were washed away or flooded.

EFFECT ON ECONOMIC PATTERN

One of the most far-reaching and long-lasting effects of the earthquake was the change that it wrought in the economic pattern of water and rail transport. Despite the fact that Anchorage is Alaska's largest city, its port business had always been relatively small as compared to that of several smaller cities. The municipally owned port facilities, in fact, had operated at a loss ever since they were built in 1961. The earthquake resulted in an enormous increase in Anchorage port facilities and commerce, and resultant decreases in traffic at the ports of Seward and Whitter and a parallel decrease in revenues for The Alaska Railroad. Weekly van-ship service was initiated from Seattle to Anchorage within a few months after the earthquake, and later experience showed that these larger vessels could surmount the ice problems that had previously kept Anchorage from being considered an all-weather port (Anchorage Daily Times, March 26, 1965).

Major changes in the economy of the region were also effected when petroleum-product terminals at Whittier and Seward were moved permanently to Anchorage. The Alaska Steamship line, one of the major cargo carriers between Seattle and Alaska, stopped calling at Seward and moved its operations to Whittier.

Devastated as it was by loss of boats, gear, and canneries, the seafood industry also underwent major changes that could only lead to its betterment over the long term. Immediately after the earthquake, salmon and crab catches at Kodiak and elsewhere were curtailed, not so much by loss of boats as by lack of processing capacity. Most seafood-processing plants were rebuilt promptly, however, and equipped with more modern machinery than they had had before. Floating canneries were introduced. Unlike property owners on land, few of whom had earthquake insurance, nearly all owners of vessels were covered by marine insurance; claims were paid promptly. The U.S. Bureau of Commercial Fisheries and the Small Business Administration lent money on easy terms for replacements of boats and processing plants. The Congress also authorized direct subsidies of as much as 55 percent for new fishing vessels. The net results were that the seafood industry obtained modern boats and better equipment and that debts were refunded at lower interest rates (U.S. Bureau of Land Management, 1964).

NAVIGATION AIDS

Many lights, buoys, tide gages, and other navigation aids were wrecked or displaced by waves, not only in the devastated harbors but along virtually all of the coastline of south-central Alaska. These aids were replaced quickly by the Coast Guard, the Navy, the Coast and Geodetic Survey, and other responsible agencies.

The Cape Hinchinbrook Light Station, on the southwest tip of Hinchinbrook Island in Prince William Sound, was severely shaken and two landslides were activated along the bluff on which the light is built, but the station remained in operation. The slides were but two more episodes in a long history of cliff erosion on Cape Hinchinbrook, and one of the few directly beneficial effects of the earthquake of 1964 was to raise the base of the cliff some 8 feet and thereby retard the erosion process. (Reuben Kachadoorian and George Plafker, written commun., 1965.)

The tectonic uplift that affected most of the Prince William Sound area resulted in shoaling of waters that had been navigable before the earthquake (fig. 1); during the first weeks after the quake some small craft were grounded or damaged by hidden rocks or were stranded by low tides. At least one cannery in the area of uplift—the Crystal Falls cannery at Mountain Slough, not far from Cordova—became inaccessible to fishermen and was declared a total loss (Alaska Dept. Fish and Game, 1965).

Tectonic subsidence in the westerly part of the earthquake-affected zone, especially around Kodiak Island and along Cook Inlet and the Kenai Peninsula, of course resulted in deeper water (fig. 1). This deeper water in itself would not have affected navigation adversely, but the subsidence also drowned old and familiar shorelines and at least locally, as in Turnagain Arm, led to increased sedimentation. The net result of subsidence, therefore, was a relatively large area of new and uncharted water.

Within hours after the earthquake, the U.S. Coast and Geodetic Survey began the difficult but essential job of recharting all navigable waterways in the area affected by the earthquake and replacing tide gages that had been destroyed. It also began a long-term geodetic resurvey of permanent horizontal and vertical changes that had taken place along shorelines and on land.

The Coast and Geodetic Survey's rapid revision of nautical charts was accomplished by ship reconnaissance, tidal surveys, and aerial photogrammetry. The resulting chart revisions, showing significant changes in channels, shoal areas, shorelines, and navigation aids were issued as "chartlets," designed to be pasted over parts of existing charts. These chartlets were upgraded as new information from more precise surveys became available. The first preliminary chartlets that were issued to navigators less then a month after the earthquake showed the harbors of Crescent City, Calif., and of Valdez, Whittier, Seward, Kodiak, and Womens Bay on Kodiak Island; chartlets of Fire Island shoal in Cook Inlet and the harbors at Anchorage and Homer soon followed. By the end of 1964, revised editions of seven nautical charts had been issued and many others, covering most of the earthquake-affected area, were made available during the next 2 years (Wood, 1966).

ANCHORAGE

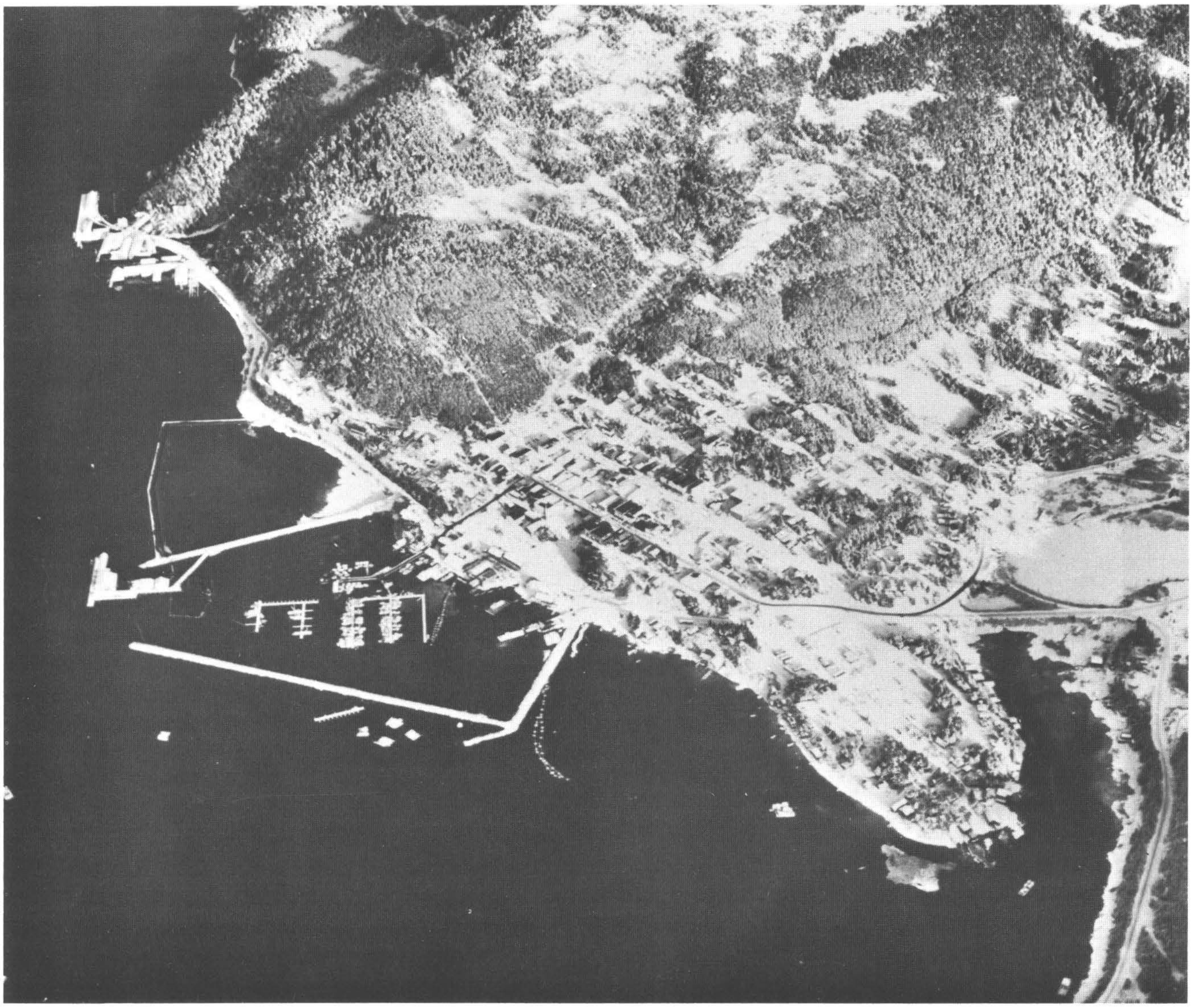
The Anchorage harbor is on Cook Inlet, just north of the mouth of Ship Creek. Port facilities, though incapacitated for a short time, were almost undamaged in contrast to all other ports in the earthquake-affected area. Tectonic subsidence was too small to do much damage, there were no waves or fires, and the bluffs above the port were not affected by the disastrous translatory landslides that wrecked several other parts of Anchorage (Hansen, 1965). Virtually all the damage to port structures was caused by earthquake vibrations and by related ground fractures and consolidation and settlement of sediments.

The municipally owned Anchorage wharf is the largest port structure (fig. 5). It consists of two adjacent reinforced-concrete docks on concrete-filled tubular piles. The joint between the two docks was opened 4–12 inches; all four cranes were shaken off their tracks, and their undercarriages and counterweight arms were damaged. The steel-frame transit shed was cracked and twisted but only to a minor degree. Some steel piles broke at their caps; battered H-piles were sprung out of line when the main dock structure shifted its position (Berg and Stratta, 1964; Alaska Construction Consultant Committee, 1964).

The so-called old Army Dock (fig. 5), a timber structure that was already much deteriorated, was made unusable for offloading of private and military petroleum supplies; a temporary petroleum dock was built to replace the old Army Dock, but it was severely damaged by ice and did not last through the following winter. Petroleum pipelines and approach roads and rail lines were broken or twisted by settlement and vibration. A cement bin, 30 feet high and 30 feet in diameter, collapsed on its pedestal. The walls of several petroleum storage tanks developed bulges at ground level. Berg and Stratta (1964) suggested that the bulges may have been caused by an earthquake-induced swirling of the tank contents, which in turn induced large vertical forces acting over a small zone at the base of the cylinder.

The port was able to handle its first ship only 3 days after the earthquake. Within 2 years, both facilities and commerce were greatly increased over preearthquake times.

5.—Anchorage municipal wharf area shortly after the earthquake, at low tide. The main dock was only slightly damaged, but the lolder Army dock (upper left), was ruined. Vibration and ground fractures damaged some structures in the port area, including the petroleum tank (lower right). U.S. Army photograph.



6.—Cordova harbor as it appeared in February 1965. Tectonic uplift left docks inaccessible to ships except at very high tides Reconstruction involved dredging of harbor and rebuilding of docks and small-boat basin. U. S. Army photograph.

CORDOVA

The Cordova area was raised about 6 feet by tectonic uplift, and the docks were thereby made inaccessible to ships except at very high tides. The deck of the main city dock was lifted and displaced by seismic sea waves and was battered by ships tied up to it. The ferry terminal dock was also damaged by waves, but these damages were insignificant as compared to the effect of regional uplift.

The city dock, ferry slip, and breakwater were rebuilt and the small-boat basin and other parts of the harbor were dredged 10 feet deeper by the U.S. Army Corps of Engineers (fig. 6). Under an urban renewal plan, the entire waterfront was rebuilt with material dredged from the harbor for fill. Much of this work involved enlargement and improvement of existing facilities rather than replacement of damaged facilities (Alaskan Construction Consultant Committee, 1964; Anchorage Daily Times, March 26, 1965). The Cordova canneries had to extend their docks an average of 110 feet to reach water depths equal to those which prevailed before the earthquake.

Because of the uplift, Orca Inlet, which is the most direct waterway from Cordova to the open sea and the important Copper River Delta salmon-fishing and clamming areas, is too shallow for all but the smallest vessels at most stages of tide. The alternative route via Orca Bay and Hinchinbrook Entrance is much longer and considerably more hazardous.

WHITTIER

The port of Whittier is at the head of Passage Canal, a western arm of Prince William Sound (fig. 1). The town was originally constructed as a military railroad terminal, having been built during World War II to serve as a backup for Seward as a second all-weather railroad port. Town and port are owned by The Alaska Railroad and the Department of Defense, but some land is privately leased.

Though many of Whittier's buildings, particularly those on bedrock, sustained but slight damage from seismic shock, the port facilities, which are on unconsolidated sediments, were so extensively damaged by the earthquake as to make them inoperable. In addition to seismic shock, other causes of damage were tectonic subsidence, ground fractures, differential subsidence due to compaction, landslides, great waves generated by submarine slides, and fire. Of these, the landslide-generated waves caused all loss of life and by far the greatest damage to port facilities. All docks were damaged or destroyed, a privately owned lumber mill was totally destroyed, and all the petroleum storage tanks along the waterfront were burned—but only after being severely damaged by seismic vibration and by waves (Kachadoorian, 1965).

Despite the extensive damage, the Whittier port facilities were back in operation in a remarkably short time, ready to aid in supplying the massive reconstruction effort elsewhere. The first train reached Whittier on April 20, was loaded at the partially repaired car slip, and returned to Anchorage. Regular weekly train-ship service, characterized by a 3-day trip between Whittier and New Westminster, B.C., began in June, less than 3 months after the disaster. Not a little of the speed with which Whittier was brought back to life was due to close cooperation between The Alaska Railroad and several military entities. Thus, while the car slip was still under repair, the Army lent a floating crane, with maximum lift of 200,000 pounds, to lift cars and vans from barges. The Navy lent a 3,000-horsepower tug to move the crane from Beaver, Oreg.; it sailed April 3 and arrived in Whittier April 13. The National Guard sent a tug from Seattle to service the crane (Fitch, 1964).

SMALLER PRINCE WILLIAM SOUND COMMUNITIES

Several smaller communities and canneries in Prince William Sound sustained varying degrees of damage from tectonic uplift and from the local violent waves of unknown origin that accompanied and immediately followed the earthquake. Damage resulting from seismic shaking or from the long-period seismic sea waves that came later was negligible (Plafker and Mayo, 1965).

Sawmill Bay on Evans Island in western Prince William Sound is the site of two operative canneries, one inoperative cannery in a poor state of repair, a fuel depot, and several permanent residences. Violent local waves that accompanied the earthquake in Sawmill Bay drowned one man, destroyed the dock of the inoperative cannery, partially damaged the fuel dock and several smaller docks, and wrecked two barges. Tectonic uplift of about 8 feet left fishing boats that had been stored on grids for the winter high above the reach of tides. The grid skidways had to be extended and some modifications to dock facilities were required before the canneries could be put back into operation.

Similar waves wiped out the entire native village of Chenega except for the school and one home and swept away 25 of its 76 inhabitants. All the minimal waterfront facilities and all but three of the boats belonging to the villagers were destroyed. The remaining population of Chenega has been relocated at Tatitlek; no repairs were made to the village site.

Other similar, but much lower, waves were experienced almost simultaneously at the inoperative canneries at Port Nellie Juan and Port Oceanic in nearby parts of the Sound. The dock of the Port Nellie Juan cannery was washed away and the cannery watchman and his family of two are missing and presumably drowned. A cannery barge 25 feet wide by 60 feet long that was tied up at the mouth of a small creek near the cannery was lifted by violent local waves, turned over end for end, moved 200 feet up the creek valley, and deposited upside down in the trees, 15 feet above high-water level. Waves at Port Oceanic destroyed the dock and washed away foundation piling from beneath the cannery; one 27-foot fishing boat that was in the bay was sunk.

At the native village of Tatitlek and the nearby inoperative Ellamar cannery, the waterfront

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7.—New small-boat basin, excavated in end of Homer Spit. Former basin, on left side of the spit, was destroyed by a small offshore slide. The fact that the entire end of the spit is submerged by high tides because of tectonic subsidence and compaction necessitates dikes around new basin. U.S. Army photograph.

facilities were impaired by about 4 feet of tectonic uplift; dredging and other improvements to the harbor area at Tatitlek by the Corps of Engineers have resulted in a harbor that is at least as good, if not better, than the preearthquake one.

HOMER

At Homer, at the mouth of Kachemak Bay on Cook Inlet (fig. 1), virtually all port facilities were put out of commission by tectonic subsidence, consolidation of sediments on Homer Spit, and an offshore landslide.

The almost new small-boat basin was completely destroyed, the timber city dock was usable but had subsided 6 feet, and oil tanks and warehouses required raising to place them above water that flooded the spit at high tides. A new and larger small-boat basin (fig. 7) was constructed by the Corps of Engineers by excavation of a part of the spit (Alaskan Construction Consultant Committee, 1964; Waller, 1966c; George and Lyle, 1966).

SEWARD

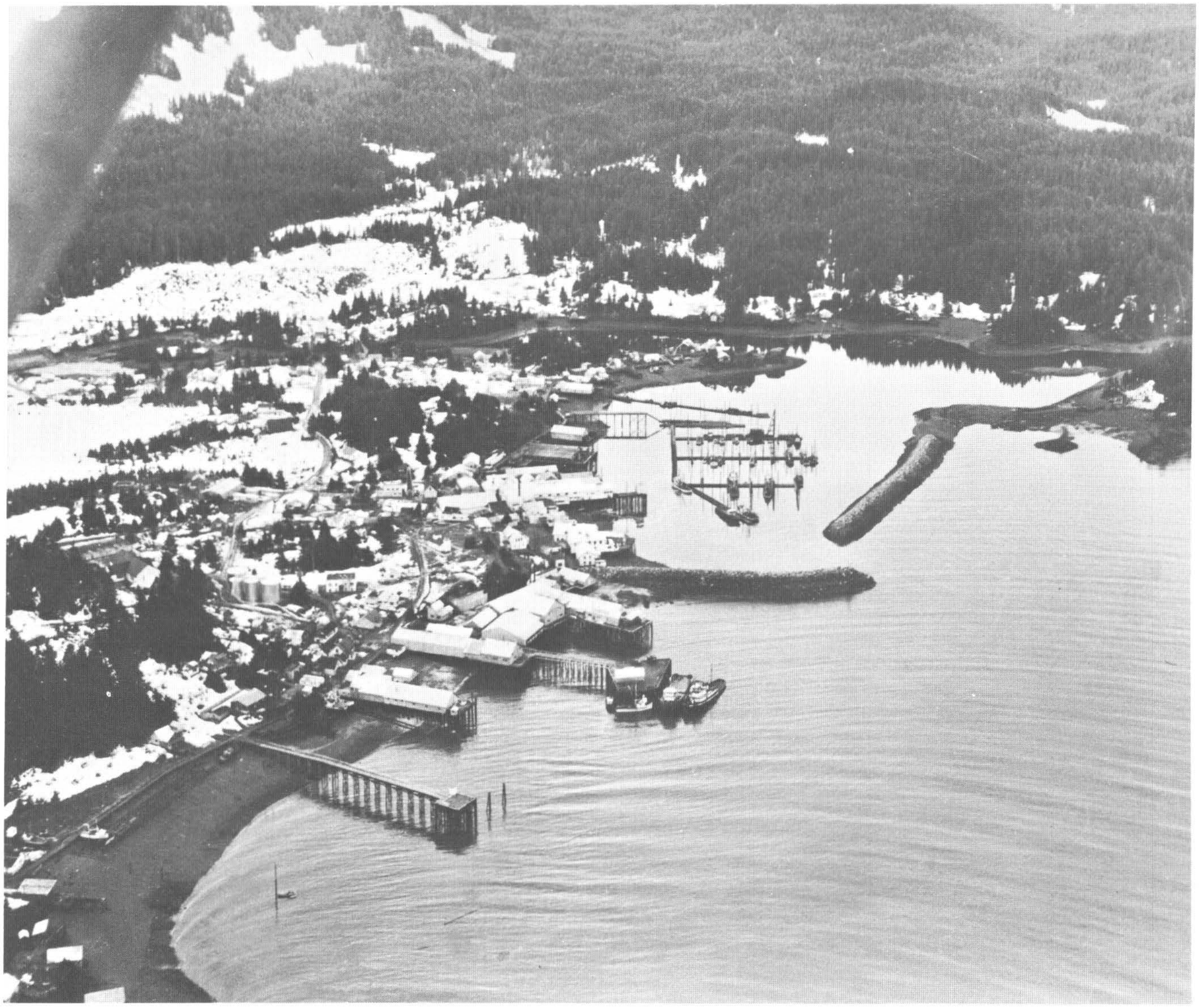
Seward, at the head of Resurrection Bay on the east side of Kenai Peninsula (fig. 1), is a fisheries center, but its main importance in the economy is as the chief year-round port for The Alaska Railroad to Anchorage and Fairbanks. All Seward's port facilities were destroyed by submarine slides, giant waves, and fire. Because both highway and rail routes were disrupted between Anchorage and Seward, the port was cut off for some days from all means of communication and transportation except radio and air travel.

Extensive geologic and soil studies of the fan delta on which Seward is built led to the conclusion that the new waterfront is unstable and subject to further submarine sliding in the event of future earthquakes. The decision was therefore made to rebuild the port elsewhere and to use the original waterfront area, under an urban renewal plan, only for parks and light industrial building. A new small-boat basin was built, and the main harbor facilities, dominated by The Alaska Railroad port terminal, were constructed on deltaic deposits at the mouth of Resurrection River, just north of the main town (fig. 8). The new site for the port required much dredging, but the chances of major submarine slides and the resultant waves are minimal (Lemke, 1967; George and Lyle, 1966).

SELDOVIA

Seldovia, a small fishing port near the southern end of the Kenai Peninsula, is the only

8.—Part of new small-boat basin and nearly completed railroad dock at Seward, November 1965. All former Seward waterfront facilities (to left of picture) were destroyed by submarine slides, waves, and fire. U.S. Army photograph.



9.—Seldovia at low tide in March 1965, with raised breakwater and small-boat basin in use. Tectonic subsidence submerged boardwalk (curving structure at shore end of docks in foreground) at high tide. The boardwalk has been replaced on new fill. Urban renewal project will alter buildings and utilities to conform with higher water levels. U.S. Army photograph.

protected harbor between Seward and Anchorage that can accommodate ocean vessels (fig. 1). Tectonic subsidence lowered the area about 3.5 feet so that most harbor facilities, including the mile-long boardwalk on which the business section of the town is built, were awash at high tides. The Corps of Engineers built a new breakwater, raised docks, and restored the small-boat harbor which had undergone subsidence and piling damage (fig. 9). An urban renewal plan was finally adopted to move the main town to higher ground, some of it to be made of fill as much as 32 feet thick (Alaskan Construction Consultant Committee, 1964; Anchorage Daily Times, March 26, 1965).

KODIAK AND KODIAK NAVAL STATION

Kodiak, near the northeast tip of Kodiak Island (fig. 1), is the headquarters of one of the largest fishing fleets in Alaska. It is best known as the center of the king crab industry, but also produces large catches of salmon, halibut, shrimp, and scallop. The nearby Kodiak Naval Station is the largest U.S. Navy installation in Alaska for both surface vessels and aircraft. The naval station was moderately damaged by the earthquake and its aftereffects, but the port of Kodiak and much of the fishing fleet were devastated—almost entirely by seismic sea waves. Neither the town nor the naval station received more than minor damage from vibration.

At the naval station, several buildings that were set on piles without adequate ties were floated away. Flooding of the power station cut off power and central steam heat for the entire facility for some days. Seismic sea waves destroyed the Navy's cargo dock, already old and deteriorated, and severely damaged the fuel pier and three structures at the crash boat harbor. Waves caused moored ships to raise the bollards and to damage fendering. Sections of the decking were lifted and displaced by waves, and some piles, placed in holes augered to the rocky bottom, were uprooted. Regional subsidence added to the toll by causing tidal inundation of the dock's remains. The marginal pier, on the peninsula side of Womens Bay, sustained only minor damage from a moored barge (Stroh, 1964; Tudor, 1964).

Tectonic subsidence left the Kodiak waterfront and the small-boat basin permanently subject to flooding by high tides. A temporary small-boat basin was established in Gibson Cove, between Kodiak and the naval station. It was used until the original basin had been rebuilt by the Corps of Engineers and its two submerged breakwaters had been raised 6 feet.

Greatest damage to the naval station and to the port of Kodiak was caused by a series of gigantic seismic sea waves, some of them non-breaking, that began about 45 minutes after the earthquake and continued far into the night. These waves destroyed or incapacitated all waterfront structures at Kodiak and inundated all of the lower part of the town. Scores of vessels were smashed or overturned and many were washed inland among flooded buildings as much as half a mile from the harbor (Plafker and Kachadoorian, 1966).

The timber city dock and its warehouse subsided and sustained wave damage, but was partly usable. Privately owned petroleum storage tanks were undamaged, but their related piers and buildings were heavily damaged or destroyed (Alaska Construction Consultant Committee, 1964). The U.S. Fish and Wildlife pier and warehouse were swept away by receding waves. The decking of the pier was lifted from the piles and the approach decking floated away. Bulkheads and about 25 piles beneath the pier were destroyed. The harbormaster's building was destroyed when a large fishing vessel collided with it. Numerous small privately owned docks on Near Channel, Potatopatch Lake, Mission Lake, and Inner Anchorage were swept away by the waves.

Of the four major seafood-processing plants, two were severely damaged and two were destroyed. Canneries at Shearwater Bay, south of Kodiak, and at Ouzinkie, north of the port, were also destroyed; the Shearwater cannery carried with it 30 salmon boats that had been in storage. Most canneries were rebuilt shortly after the earthquake, and floating canneries were brought in to add to the industry's capabilities. Docks and buildings at four other operative canneries within the zone of tectonic subsidence had to be raised above the new higher extreme high-tide level (Plafker and Kachadoorian, 1966).

Docks at two small lumber mills near Afognak and Ouzinkie were also damaged by the seismic sea waves.

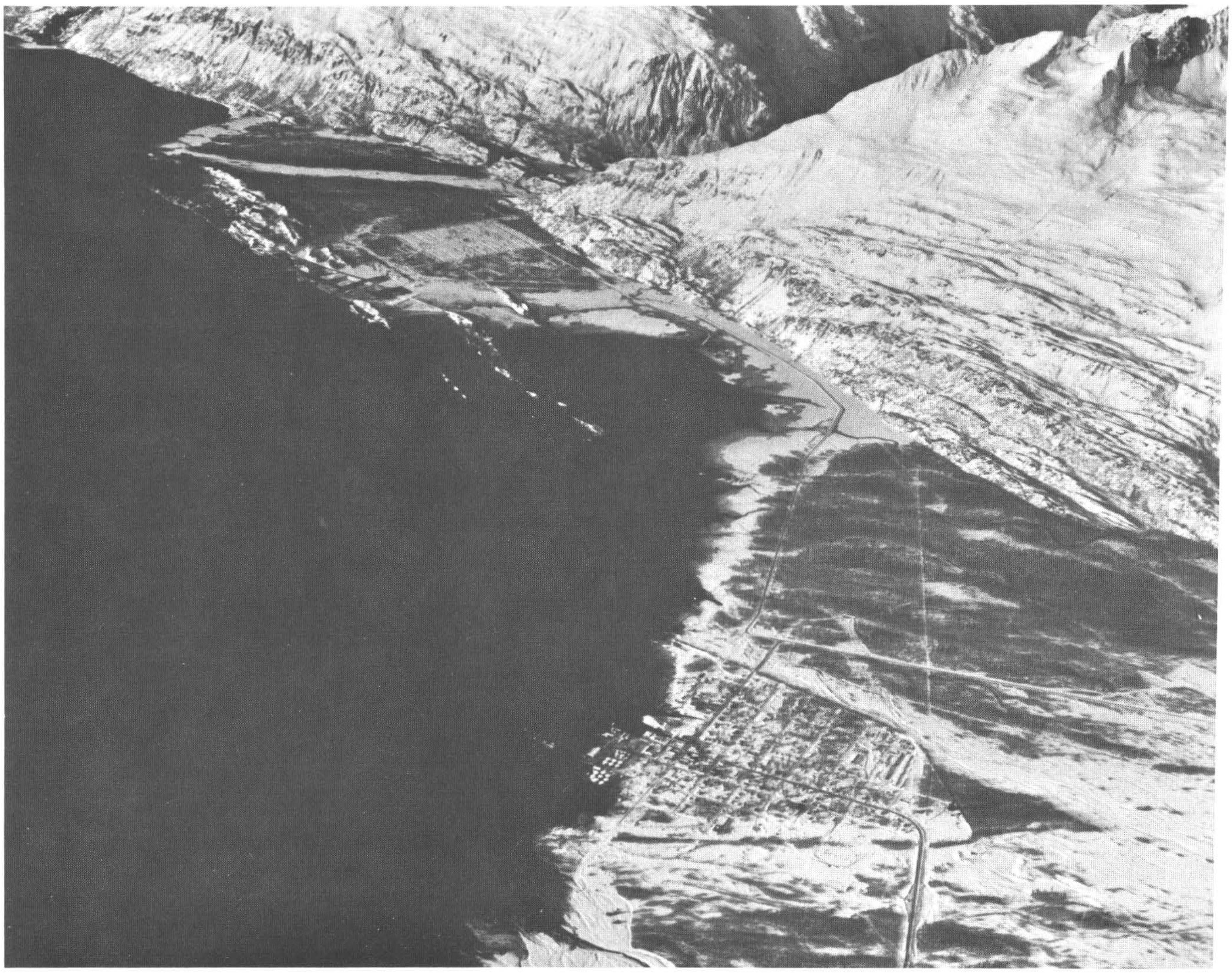
A Navy seaplane tender was sent from Oak Harbor, Wash. Arriving on March 31, 1964, it immediately hooked its generators to naval station lines and supplied a part of the station's power needs for some days. The Navy also brought a dock landing ship, with a 160-foot pontoon dock from San Diego. It was lent to the city of Kodiak to help in rehabilitation of the fishing fleet (Kachadoorian and Plafker, 1967; Stroh, 1964; Tudor, 1964).

VALDEZ

Valdez is the northernmost all-weather port in Alaska. Unlike Seward and Whittier, which are also all-weather ports, it is not a railhead but is connected with Fairbanks and the interior by highway. The town is on Port Valdez, the northeasternmost extension of Prince William Sound (fig. 1).

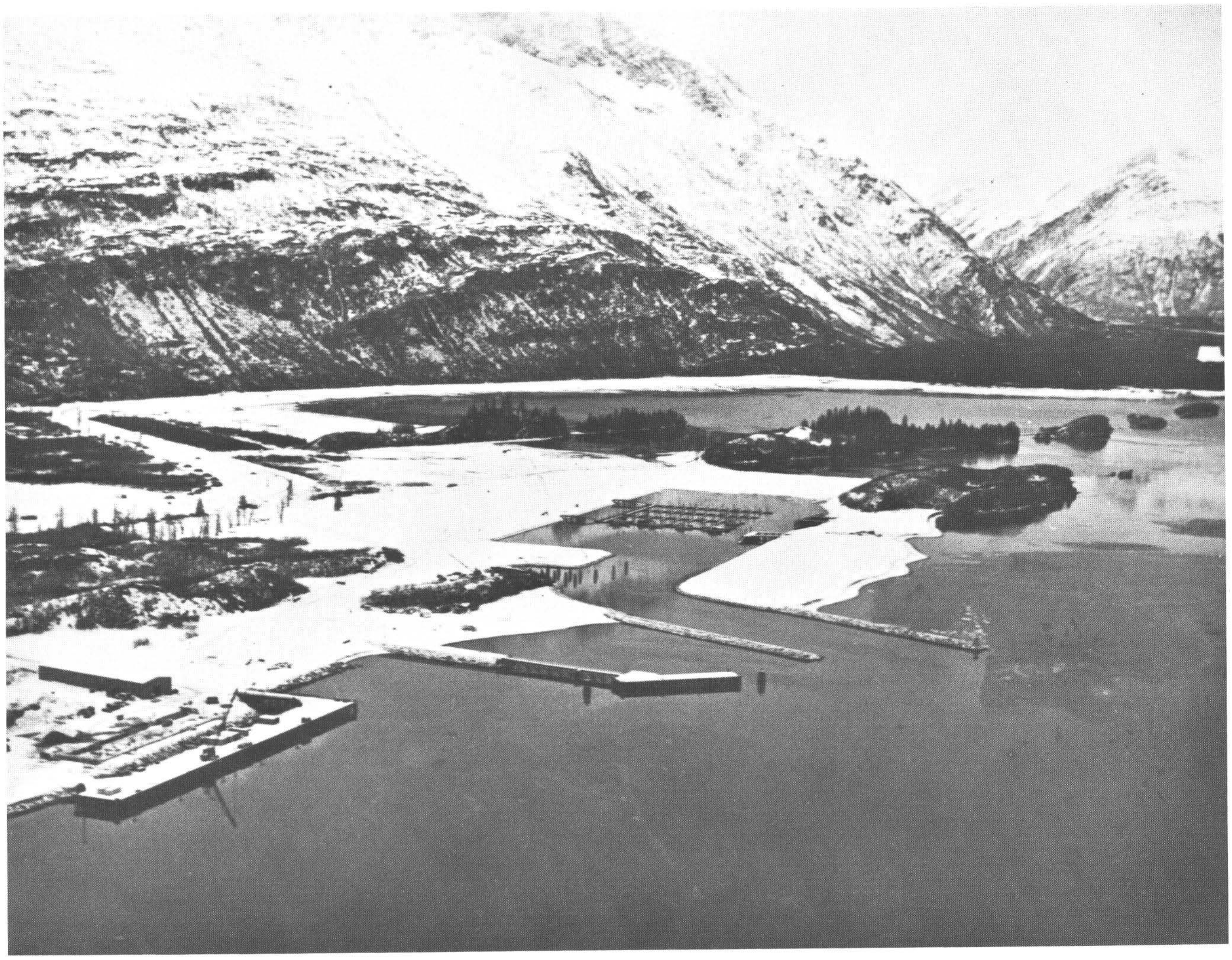
All port facilities were destroyed by the earthquake (fig. 10). A gigantic submarine slide off the face of the delta on which Valdez is built was the single most disastrous event—it completely destroyed all docks and superstructures. Waves, ground cracks, shaking, and fire left all other port facilities and the seaward part of the town in ruins.

Shortly after the earthquake, the Corps of Engineers built a temporary dock on the newly formed waterfront, primarily for



10.—Old and new Valdez. All waterfront structures and utilities in old Valdez were destroyed (lower center). The new townsite (upper left) is protected from slides by chain of bedrock hills. U.S. Army photograph.

offloading of supplies needed in rehabilitation of the town but also to permit the small commercial and sport-fishing industries to resume work. Meanwhile, the likelihood of further submarine slides and continued settlement along the waterfront, and the danger of flooding by the Valdez glacier stream that built the delta, led geologists to advise complete abandonment of Valdez. This advice was followed by town officials who decided to build a new town at Mineral Point, about 4 miles by road west of the devastated community. The new site is far less likely than the old to be damaged by future earthquakes, and the modern docks and ferry slip that will allow Valdez to resume its place among Alaskan ports are founded on bedrock that is not susceptible to underwater slides (figs. 10, 11; Coulter and Migliaccio, 1966).



11.—Harbor facilities at new town of Valdez, winter 1966. Townsite is just to left of picture, behind protective bedrock hills. U.S. Army photograph.

COMMUNICATIONS AND UTILITIES

To an extent that is seldom realized except when they are disrupted, modern man depends on public utilities and communications. All are necessary for his comfort and survival within his own community and for ties with other communities—water, sewage disposal, power and heat, and radio, telephone, and television communication. In Alaska's subarctic climate, reliable sources of heat and power are even more important than they are elsewhere. Communications facilities, too, are more vital in Alaska than elsewhere, for much of the population is thinly scattered and in poorly accessible places and also because Alaska itself is far removed from the rest of the United States.

Virtually all utilities and communications in south-central Alaska were damaged or wrecked by the great earthquake. The total cost of damages to utility systems was initially estimated to be about $25 million (Alaska Construction Consultant Committee, 1964). This figure is small in comparison to the total cost of the earthquake, and fails to give a true picture of the emotional and physical effects wrought by disrupted utilities and communications during the recovery and rehabilitation periods. Predictably, utilities at Anchorage and its neighboring military establishments represented at least two-thirds of the total losses. This high proportion was only because Anchorage is the largest community, with consequently greater development of utilities. Several other towns lost greater proportions of their utility systems than did Anchorage.

Complete repairs and replacements required many months of effort, but essential services that sufficed to alleviate panic and suffering and to prevent disease that commonly follows on disruption of utilities were restored in a short time. This fast restoration was due to the prodigious cooperative efforts of the utility suppliers, both private and public, working in conjunction with the military and civilian authorities (U.S. Army Alaskan Command, 1964).

Because they tend to be widespread geographically, rather than confined to single towns, the communications system, the oil- and gas-distribution facilities, and the power systems are described separately. These generalizations are followed by descriptions of the effects on all utility systems in certain towns.

COMMUNICATIONS SYSTEMS

South-central Alaska has a well-developed communications system—telephone, radio and television. Because of the great land and water distances and the mountainous terrain, greater dependence is placed on radio and radiotelephone facilities than elsewhere in the United States.

Most telephone lines are above ground, though in parts of Anchorage and in some of the rugged mountains both military and civilian lines are in buried cables. Nearly all telephone communications were disrupted by loss of power soon after the onset of the earthquake. In a few places, services were restored almost immediately by use of batteries or other auxiliary power units. Elsewhere, however, central stations were severely shaken or were wrecked by waves and other aftereffects of the earthquake shocks.

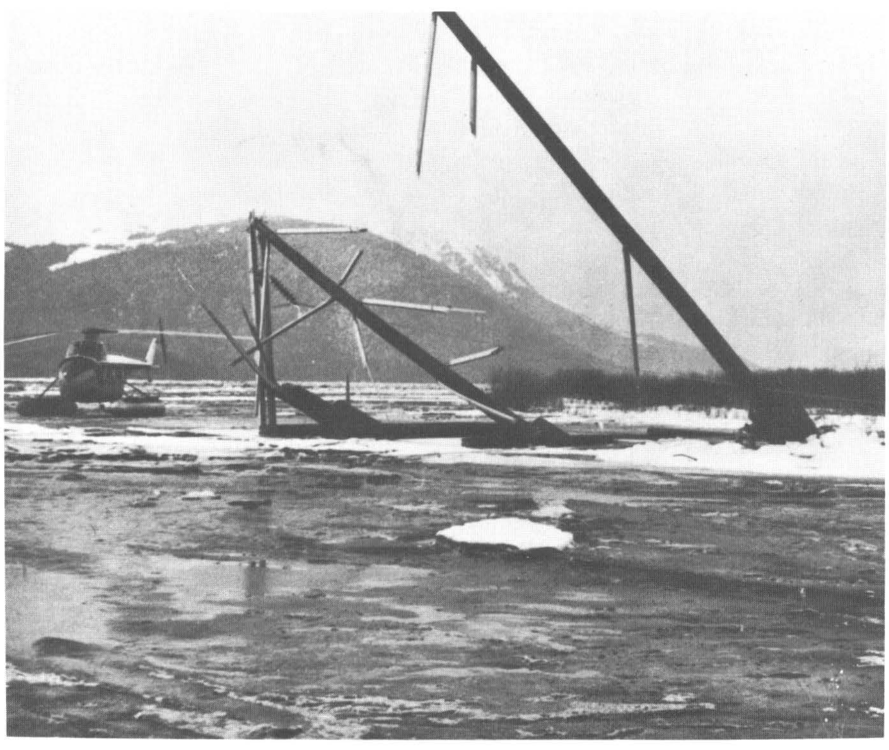
Overhead lines, both power and telephone, sustained much damage from the shaking. Tautened wires broke in tension. Utility poles were subject to the same whipping action as trees, but because they were less resilient a greater proportion of them were broken. Other poles survived the shaking itself but were brought down by avalanches or landslides. Still others, as in Turnagain Arm, were wrecked when the silt in which they were placed shifted on the sea bottom (figs. 12, 13).

Despite the widespread damages and a great variety of problems, most telephone systems were fully or partially restored to service within a few hours of the earthquake.

Nearly all commercial and military radio and television communications went off the air immediately as a result of power failures. While power was being restored, they were replaced temporarily by a fantastic patchwork of amateur radios in Alaska and the conterminous United States, mobile broadcast units, and short-wave transmitters in ships, taxis, parked planes, police cars, and many other vehicles and places. These means served well in reestablishing contacts with isolated communities and with the outside world, in getting relief and reconstruction underway, and in preventing panic.

Firefighting organizations and their equipment remained intact in all the earthquake-affected

12.—Power and telephone poles along Turnagain Arm were tipped when the silt in which they were embedded was liquefied by earthquake vibrations. Photograph by Chugach Electric Association, Inc.



13.—Some power-transmission poles on Turnagain Arm were destroyed by liquefaction of silt foundation and by floating ice. Photograph by Chugach Electric Association, Inc.

towns, but disruption of water supplies made them virtually useless in Seward, Valdez, and Whittier, where large waterfront fires developed; they would also have been helpless in Anchorage had there been fires. The readiness of all fire departments was also hampered by difficulties in communications (National Board of Fire Underwriters, 1964).

POWER SYSTEMS IN ANCHORAGE, THE MATANUSKA VALLEY, AND ON THE KENAI PENINSULA

In the general vicinity of Anchorage, electric power is provided from four sources—(1) a city-owned steam generating system, (2) military-operated steamplants that serve Fort Richardson and Elmendorf Air Base, (3) the Bureau of Reclamation's Eklutna hydroelectric project, serving Palmer, the Matanuska Valley, parts of Anchorage, and (4) the Chugach Electric Association's hydro- and steam-power generation system serving part of Anchorage and most communities on the Kenai Peninsula (fig. 1).

All these systems were damaged, some severely, by the earthquake of March 27, 1964. Though disastrous and expensive, the power-system failures were fortunate in some ways. The fact that power was shut off immediately in Anchorage, for example, is widely credited for the almost complete lack of fires there. Virtually all of the damage to transmission lines was of the kind ordinarily expected during Alaskan winters, but damage was more widely scattered geographically and far more concentrated in time than usual. These conditions made repair work much more difficult and costly than normal, even though most of the maintenance problems were familiar ones.

Earthquake damages to the Eklutna hydroelectric system, caused almost entirely by ground vibration and related cracks and subsidence, are described by Logan (1967).

The military powerplants at Fort Richardson and Elmendorf Air Base use coal-fired steam turbines. Both systems sustained much structural damage from seismic vibration. Tanks, piping, and other equipment were distorted or broken by twisting, overturning, or failure of supports. Despite the widespread damages, central heating for the military bases was maintained with almost no interruption, and power was restored to large parts of both bases within 24 hours (Powers, 1965; U.S. Army Alaskan Command, 1964; Stephenson, 1964).

Parts of Anchorage, including the heavily damaged Turnagain Heights section, and most of the Kenai Peninsula are served power by the Chugach Electric Association, a cooperative financed by the Rural Electrification Administration. Much of the rather complex integrated system was heavily damaged by the earthquake, but ties with other power sources and close cooperation of all suppliers, military and civilian, resulted in restoration of power to most of the affected areas within a very few days.

Principal units of the Chugach system are the Knik Arm coal-fired steamplant near the mouth of Ship Creek in Anchorage, the Bernice Lake gas turbine plant just north of Kenai (fig. 1), and the Cooper Lake hydroelectric plant. The Cooper Lake generating plant is actually on the south shore of Kenai Lake, but it drops water from nearby Cooper Lake through a mile long tunnel and a penstock. The Knik Arm and Bernice Lake plants produce some steam for local distribution in addition to electricity. Bernice Lake supplies power to several communities on the Kenai Peninsula, including Homer, which also has a diesel-electric generating plant. Seward is served power from Cooper Lake.

Except for vibration damage to turbine blades at Bernice Lake, neither this nor the Cooper Lake plant was seriously injured. Failure of the power system in the Anchorage area overloaded the entire transmission network and caused automatic overload switches to trip at the other generating plants. Because Anchorage was closer to the epicentral region in northern Prince William Sound, failures there occurred an estimated 15–20 seconds before the tremors were first felt at the Bernice Lake plant; this time lapse was enough to allow the plant operator to shut off the power before the potentially damaging vibrations reached the plant. The Knik Arm plant, however, was severely shaken, and coal bunkers, ash handling system, and other structural elements were either weakened or destroyed. The most serious damage was not noticed until 2 weeks after the earthquake when high tides made apparent the fact that tectonic subsidence and local compaction had lowered the mouth of Ship Creek. Sea water flooded the cooling pond and the ash aisle in the basement of the plant.

Damages to the Chugach distribution system were less severe than to the generating plants but were nevertheless substantial. About 50 poles broke and 25 transformers were dropped to the ground. Underground lines and several substations in downtown Anchorage were destroyed by landslides (Chugach Electric Assoc., 1964).

In Palmer and the surrounding Matanuska Valley, northeast of Anchorage, power outage lasted for 18 hours. The distribution system itself was undamaged, but the transmission line from the Eklutna plant was downed by an avalanche near the Knik River (Logan, 1967).

Automatic vibration controls reacted to the first earthquake shocks to shut down the Anchorage municipal gas-turbine plant. The plant itself survived in good condition, but breaks in the gasline cut off the fuel supply. Six standby diesel generators were also inoperative because water-main breaks stopped the supply of cooling water. Some intermittent power was restored to the city within 2½ hours after the earthquake, when the turbine plant was started with bottled gas and then converted to oil for fuel. Rupture of oil tanks, with consequent loss of fuel, caused further delays in delivery of firm power, but an emergency supply of oil from Elmendorf Air Base was used until the gaslines were repaired. As a result, power was restored to nearly all of Anchorage by midnight Sunday, March 29. The municipal power-distribution system, both aerial and underground, was almost undamaged except in the slide areas. Two substations were wrecked by slides and had to be relocated (Stephenson, 1964).

Most substations sustained light to moderate damage from vibration. Transmission and distribution lines were disrupted in many places. In the Turnagain section and elsewhere in Anchorage, lines were broken by the gigantic translatory landslides that were the principal geologic effects of the earthquake there (Hansen, 1965). The transmission line along the north side of Turnagain Arm, particularly between Girdwood and Portage, was very severely damaged—13 tower structures were destroyed and 60 others required extensive repairs. Most of the structures tipped or broke when the silt in in which they were embedded was liquefied by vibration, but later the tidal action and increased ice shove that resulted from tectonic subsidence of the area did further damage (figs. 12, 13). In the mountains, earthquake-triggered avalanches destroyed several towers on the line between Portage and Cooper Lake and between Cooper Lake and Seward (Chugach Electric Assoc., 1964).

PETROLEUM AND NATURAL GAS FACILITIES

Alaska depends as heavily as any other modern society on petroleum products and on natural gas for heat, power, and transportation. Most of the petroleum products used in Alaska are brought in by water from West Coast refineries or from fields in Cook Inlet and along its shores (fig. 1). Like all other water-transported goods, fuel supplies were disrupted and dislocated by destruction of most of the ports in south-central Alaska. In addition to water transport, however, three pipe lines play significant parts in transmission of petroleum and gas products; none of these was appreciably damaged.

A single leak developed in the 93-mile line that transmits natural gas from fields near Kenai to Anchorage. An 18-mile pipeline (not shown on fig. 1) transmits crude oil from wells on the Swanson River and Soldatna Creek, on the Kenai peninsula, to loading facilities at Nikishka on Cook Inlet. The line itself was unscathed but storage tanks at the terminal were slightly damaged. A few leaks also developed in storage tanks at a small refinery near Nikishka but they were easily repaired (Office of Emergency planning, 1964).

A military multiproduct pipeline, much of it above ground, extends 686 miles from Haines in southeastern Alaska, to Fairbanks. Roughly parallel to the Alcan Highway, it handles more military petroleum products than does the port of Anchorage. Far from the area of disturbance, the pipeline was not damaged by the earthquake and service was not interrupted. Water wells at a few of the booster stations, however, were slightly damaged.

Many storage tanks, notably in Anchorage, Seward, Valdez, and Kodiak, developed leaks from earthquake vibration or were totally destroyed by waves or fire. Quick repairs to tank farms, and early resumption of water transport for fuel supplies, prevented development of critical shortages of petroleum products.

Many homes and businesses throughout the stricken area depend on individual bottled-gas units for heating. Fortunately, very few of these installations were damaged outside the areas of total destruction caused by waves, fires, and landslides. Piped natural gas is available only in Anchorage and several small towns near Kenai. The damages to this system, and the methods used to restore service, are well documented by Stump (1965), from whose paper most of the following information is abstracted.

The natural gas used by Anchorage is produced from the Kenai field near Kalifonsky Beach on Cook Inlet. It is supplied by the privately owned Anchorage Natural Gas Corp. and its sister organization, The Alaska Pipeline Co.

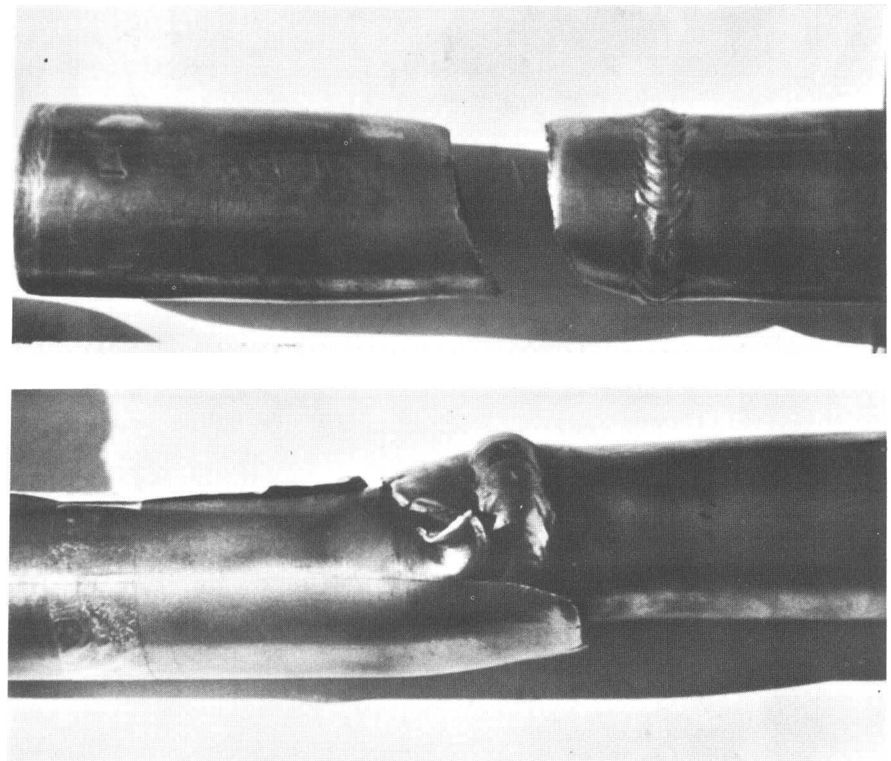
A 12-inch pipeline, 93 miles long, brings gas to Anchorage (fig. 1). Much of the line is in rugged country that is accessible only by tracked vehicles or by air. There are three airstrips along the right-of-way, which is itself cleared to permit use of helicopters. The 8-mile-long segment across Turnagain Arm, 30 miles south of Anchorage, has parallel pipelines that are embedded in the silt of the Arm. The earthquake caused little damage to the underwater line, but tectonic subsidence in the area necessitated raising the automatic control valves above the new high-tide levels. Only one small but potentially serious break occurred in the entire pipeline. This one, doubtless caused by ground vibration, was at milepost 55 and consisted of a circumferential crack next to a weld in the pipe. Access was difficult but, once reached, the break was easily and quickly repaired.

Damages to the 120-mile-long gas-distribution system within Anchorage amounted to nearly $1 million, a heavy blow to a company that was less than 3 years old and was just beginning to reach financial stability. Nevertheless, there was far less damage to this entirely new system whose components were all designed and constructed to modern code specifications than there would have been to old or poorly built equipment. As would be expected, most major breaks in the distribution system occurred at landslide grabens where near-surface materials moved both laterally and vertically (Hansen, 1965). Some of the more than 200 breaks in gaslines, however, were caused by ground cracks which had little or no visible displacement. Steel and copper pipes reacted similarly to the earthquake forces. Some lines failed in compression or tension; others failed by shear or by repeated flexing (fig. 14).

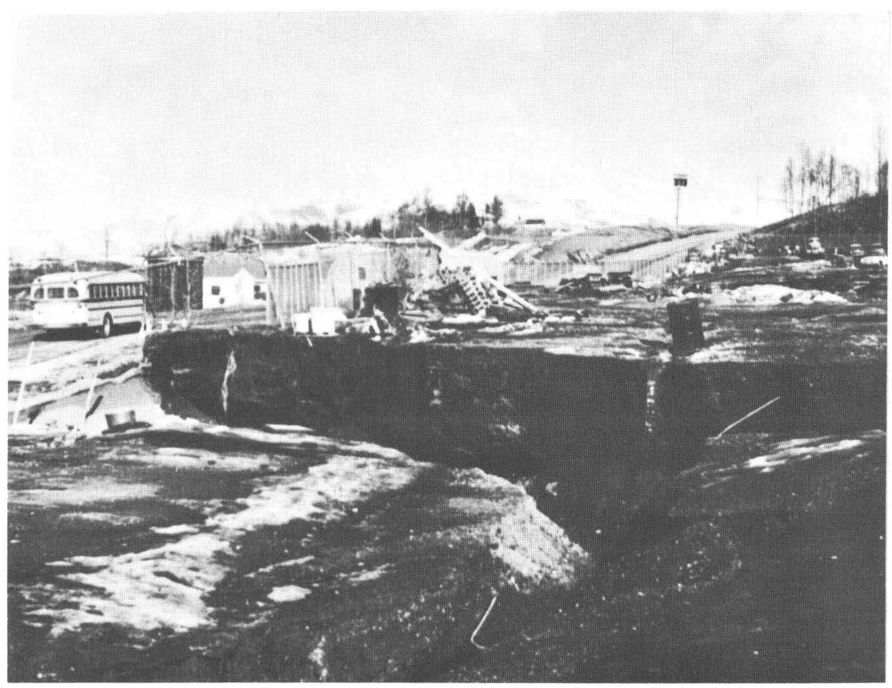
In Anchorage, the high-pressure gas main was broken by the landslide at Third Avenue and Post Road, near the Alaska Native Hospital (fig. 15). A second break in the main was caused by a slide near the Municipal Power and Light Plant on Ship Creek. This slide ruptured fuel tanks and flooded the area with 300,000 gallons of diesel fuel.

The making of repairs was greatly aided by the loan of experts from several natural-gas companies in the Pacific Northwest; priorities were given to the city powerplant, hospitals, restaurants, and laundries, in that order. Gas service was restored to the municipal powerplant within 30 hours after the earthquake, a remarkable accomplishment considering that temporary lines had to be laid on steep slopes and on a surface that was covered by ice and by a thick layer of diesel oil. The city's two gas-fired turbines furnished most of the electric power for Anchorage for some weeks. Gas became available in homes and businesses in Spenard and the southern part of Anchorage within 48 hours, and 90 percent of the entire system was restored within 2 weeks after the earthquake.

During the spring and summer of 1964, and after all known leaks had been repaired and service restored, the company made a novel use of geologic maps. The ground in Anchorage was frozen to depths of 6 feet or more at the time of the earthquake, and buried pipes could not move or adjust to stresses except at ground breaks. The pipes therefore



14.—Buried gaslines ruptured by earthquake forces. Above, in tension; below, in compression. Photographs by W. J. Stump.



15.—Twelve-inch gas main, supplying fuel for municipal powerplant, was ruptured by landslide at Third Avenue and Post Road, Anchorage. Photograph by W. J. Stump.

required relief from stresses imposed by the earthquake, because these stresses, plus those that would be imposed by future thawing and frost action, would undoubtedly cause additional failures in the system.

All excavations where repairs had been performed on gas, sewer, and water lines were mapped by the gas company, and the assumption was made that stresses had been relieved in these areas. Maps prepared by the Engineering Geology Evaluation Group (1964) were then used in conjunction with the company's accurate as-built maps and records of its distribution system. By studying the two sets of maps, about 50 places were identified where earthquake-caused ground fractures meant that there must be residual stresses in the gaslines. At the center of each such area the line was exposed and cut. Some pipes were under such tension that the cuts opened as much as 2 inches; elsewhere compressive forces shortened the pipes. Successive exposures and cuts in the lines were then made at 50-foot intervals away from the origins until points were reached where cuts resulted in no movement of the pipes. The same method was used for the transmission line. The entire line was examined by helicopter traverse. Wherever ground cracks were observed to cross the line, excavations were made to allow the pipe to move and thus relieve residual stresses.

ANCHORAGE

Much of the following information on Anchorage public utilities is taken from Stephenson's report (1964).

Except for radio and television, which were interrupted only because of lack of electric power, all public-utility systems in Anchorage were affected similarly by the earthquake but in somewhat varying degrees. All utilities that depended on underground transmission or distribution—telephone, water, sewer, power, and gas—were disrupted when lines were broken by landslides and earth fissures.

Anchorage and the nearby military posts obtain water by diversions from Ship Creek and from a few deep wells. There are also some shallow private wells, mainly in the suburbs. In order to take advantage of the extra heat available in ground water, the wells are used more extensively in winter than in summer.

The earthquake caused moderate damage to the city treatment plant, and several of the wells were destroyed by ground movements. Ground-water levels dropped temporarily and water from many wells was muddy. The Ship Creek supply was cut off for a short time when an avalanche blocked the stream above the diversion points, but water was restored to the system when the temporary dam was overtopped and cut through by natural streamflow (Waller, 1966b).

By far the greatest damage to the Anchorage water system was in the distribution system, where ground fractures and landslides broke pipes in nearly 100 places. All types of pipe were affected by these ground movements. Immediately after the earthquake the delivery rate nearly quadrupled because of the numerous breaks in the lines. It was necessary to shut off the supply completely and to repair it section by section.

Service was restored to more than half of Anchorage within the first 5 days, and most of the city had water within 2 weeks. Much of the repair work was of a temporary nature. Firehose and portable pumps and chlorinators were used first, but these were soon replaced in the Turnagain and port areas, and to a lesser extent elsewhere, by aluminum irrigation pipe laid on the surface and connected to dwellings with garden hoses. Completion of more permanent repairs to the underground systems required many months, in part because of the havoc caused by landslides in parts of the city and in part by the necessary delays for exploration of the slide areas and for planning how they should be treated. (Alaska Depart. Health and Welfare, 1964; Waller, 1966b; Stephenson, 1964).

Except for the Spenard area, which has a treatment plant, the Anchorage and nearby military sewage systems discharge untreated wastes directly to Knik Arm. Outfalls were damaged by earthquake vibration and required replacement. The underground systems, built primarily with concrete pipe, were broken by landslides, earth cracks, and vibration in a manner and in places similar to the breaks in the water-supply systems (Stephenson, 1964; Alaska Depart. Health and Welfare, 1964). A portable television camera was used effectively to find breaks in the sewer lines (Burton, in Logan, 1967).

The central telephone office in downtown Anchorage was severely shaken and fuses were blown. In the Alaska Communications System toll building on Government Hill, two 15-ton battery plants collapsed by shaking and caught fire, but the fire was quickly controlled.

The aerial wire system, which serves most of Anchorage, sustained only minor damage except where poles were broken or dislodged by landslides. In contrast to underground powerlines, however, which were only slightly damaged, almost all of the 25-mile underground telephone-cable system in downtown Anchorage was put out of commission. Tension, caused by stretching of the ground incident to ground cracks and landslides, pulled the cables away from manhole connections.

CORDOVA

Utilities in the main residential area and business district of Cordova—a town built almost entirely on indurated bedrock—were unaffected by the tremors. Slight damage was sustained by utilities in the waterfront area, mainly as a result of shifting of the docks and piers on which the utilities were located and of inundation of low-lying areas. All utilities functioned continuously throughout the earthquake. Minimal damage resulted from tectonic uplift that left sewage outfalls above high tides (Office of Emergency Planning, 1964).

Utilities at the Cordova airport which is on thick alluvial deposits 13 miles from the town, were disrupted by vibration and ground fractures. Overhead powerlines were snapped by violent motions of their poles, and underground steam, water, and sewer pipes were broken and made inoperative by innumerable ground cracks.

Cordova depends largely on diverted surface water for its water supply; but also has two deep standby wells. Earthquake damage to the distribution system and to the sewer system was minimal except for the fracturing of pipes in the waterfront area and at the airport.

KODIAK

Communications facilities at Kodiak Naval Station were hard hit. Except for Fleet Weather Central, which required less than 5 minutes to convert to standby power sources, naval station communications were without power for some hours. Not only was the central powerplant inoperative, but 2½ miles of line between the station and the radio transmitter had been washed out by waves. Generators for Operations Control and for the Tactical Air Command and Navigation centers were also damaged.

In the town of Kodiak, the central telephone office was flooded, and the line to a long-distance radio-telephone transmitter atop Pillar Mountain was downed by earthquake shocks. Long-distance communications with the mainland were reestablished the morning after the quake, but for 3 weeks the only local communications were supplied by a few portable field telephones and by short-wave radios in taxicabs and police vehicles. Within a month after the earthquake about 100 telephone circuits had been restored (Tudor, 1964; National Board of Fire Underwriters, 1964; Kachadoorian and Plafker, 1967).

The powerplant at Kodiak Naval Station was repeatedly flooded by waves and electricity and steam heat for the entire installation was cut off. Emergency generators on land and on a seaplane tender that was rushed from Whidby Sound, Wash. (Kasperick, 1964), supplied partial needs for power to the station for 2 weeks while the main plant was being repaired. A massive power failure occurred in the town of Kodiak at 5:39± p.m. This failure was during the early phase of the seismic shaking. Automatic equipment in the Kodiak Electric Association generating plant made four unsuccessful attempts in 3 seconds to reclose the circuits. Flashes were emanating from the plant, and the power failure resulted apparently from a short circuit at the generating plant rather than in the feeder or distribution line. Had the power failure not occurred before the first seismic sea wave struck the city of Kodiak, the inundating waves would undoubtedly have caused failure.

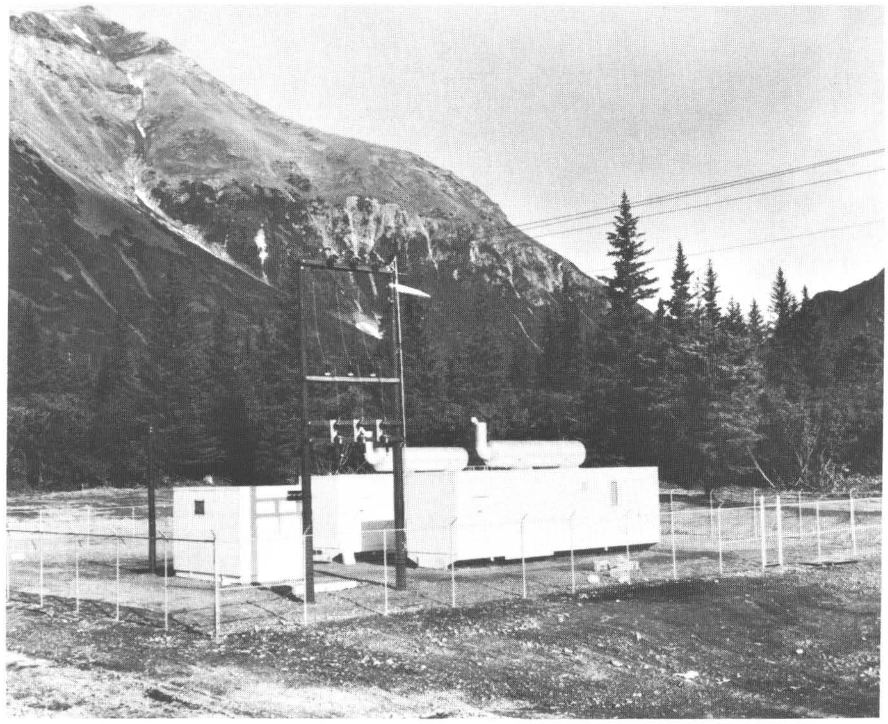
Kodiak's water and sewage lines were cracked in a few places by earthquake vibration, but they sustained very little damage except in the lower part of town that was destroyed by seismic sea waves. Kodiak is served by two water reservoirs north of town. One of these was very slightly damaged by shaking and both reservoirs were closed for a few hours after the earthquake to conserve water for fighting fires that were expected but fortunately did not materialize. Service of untreated water was restored the day after the quake, and chlorination of water was restored on March 29 (F. R. B. Norton and J. E. Haas, written commun., 1966; Alaska Depart. Health and Welfare, 1964).

The Kodiak sewage system was affected similarly to the water distribution system; that is, it sustained only minor damage except near the waterfront where it was severely damaged. Tectonic submergence of the shoreline (Kachadoorian and Plafker, 1967) lowered the sewage pumping station to such an extent that it had to be replaced.

SEWARD

Submarine slides and giant waves destroyed Seward's port facilities, including utility systems near the waterfront. In addition, vibration and ground fractures disrupted water and sewer lines in many other parts of town and in suburban Forest Acres (Lemke, 1967).

Seward is served power by the Chugach Electric Association from its Cooper Lake hydroelectric plant; transmission-line damages disrupted the service. Temporary restoration of part of the power was effected in May 1964 by the installation of small portable generators. The distribution system was repaired by November of the same year, and a new standby city powerplant (fig. 16) was completed in 1965 (Lemke, 1967; office of Emergency Planning, 1964; Chugach Electric Assoc., Inc., 1964). The Seward telephone system was completely disrupted for a few hours, and service was spasmodic for some weeks after the earthquake. Batteries were used early in the emergency period, but portable generators were installed later (National Board of Fire Underwriters, 1964).



16.—Emergency standby generators at Seward, August 1965. Seward normally receives power from Cooper Lake hydroelectric plant, but all power was cut off by the earthquake. U.S. Army photograph.

Seward obtains most of its water by diversion from Jap and Marathon Creeks, and it also had four deep wells. Three of the wells were put out of operation by earthquake shaking, but the surface supplies survived with only minor damage. Both water and sewer lines sustained breaks in many places throughout Seward and the suburban areas, and water service was cut off for periods ranging from 12 hours to more than a week after the earthquake. These damages, however, were minor as compared to those in the port area, where all facilities, including water mains and sewage outfalls, were completely destroyed by submarine slides and waves (Lemke, 1967; Alaska Dept. Health and Welfare, 1964). An emergency salt-water system that might have helped in controlling the subsequent fires was inoperable because its waterfront pump station was wrecked (National Board of Fire Underwriters, 1964).

VALDEZ

Before the earthquake, Valdez was served water from two deep wells close to the town. Neither the wells nor the elevated storage tank adjacent to them were damaged, but water and sewage lines throughout the town were broken by ground fractures in many places. Total destruction of the waterfront by a gigantic submarine slide of course wrecked waterlines and sewer outfalls completely in that area (Coulter and Migliaccio, 1966). Local telephones remained in service, except for the strip along the waterfront. The powerplant, also, was undamaged. A few distribution lines fell, but the power supply was continuous to most parts of town except the waterfront (National Board of Fire Underwriters, 1964). Because of the decision to abandon the townsite and to rebuild Valdez elsewhere, only temporary repairs were made to the systems.

Design and construction of modern underground utilities at the new townsite were based in part on knowledge of earthquake response of various materials gained by study of damages at Anchorage, old Valdez, and elsewhere. The principles of utilities design in an earthquake-prone region that is also subject to heavy snow cover and deep frost penetration are described by Poirot (1965).

WHITTIER

Most of Whittier's water is obtained by impoundment of Cove Creek, backed up by two drilled standby wells. These sources were not materially damaged by the earthquake, but the distribution system and the outfall sewer system were damaged extensively—especially in the port area—by shaking, ground fractures, and landslide-generated waves (Kachadoorian, 1965; Alaska Depart. Health and Welfare, 1964). A deep well at the head of Passage Canal was ruined by extrusion of the casing and well head as a result of differential compaction and by flooding of the site at high tides.

The powerplant was shut down during the earthquake when two 10-inch waterlines from the Cove Creek impoundment were broken. The plant was instantly switched to standby auxiliary generators which supplied emergency power for a period of 6 hours, until the main plant was put back into operation with water pumped through a firehose from Passage Canal. The powerplant itself, which is on a foundation of solid rock, was virtually undamaged by the earthquake. However, some of the feeder lines that were destroyed along the inundated waterfront area had to be either repaired or cut off the circuit before full power could be restored.

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